

Orbital Kondo effect in a parallel double quantum dot

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Abstract. We construct a theoretical model to study the orbital Kondo effect in a parallel double quantum dot (DQD). Recently, pseudospin-resolved transport spectroscopy of the orbital Kondo effect in a DQD has been experimentally reported. The experiment revealed that when interdot tunneling is ignored, there exist two and one Kondo peaks in the conductance-bias curve for the pseudospin-non-resolved and pseudospin-resolved cases, respectively. Our theoretical studies reproduce this experimental result. We also investigate the situation of all lead voltages being non-equal (the complete pseudospin-resolved case), and find that there are four Kondo peaks at most in the curve of the conductance versus the pseudospin splitting energy. When the interdot tunneling is introduced, some new Kondo peaks and dips can emerge. Besides, the pseudospin transport and the pseudospin flipping current are also studied in the DQD system. Since the pseudospin transport is much easier to be controlled and measured than the real spin transport, it can be used to study the physical phenomenon related to the spin transport.

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1. Introduction

The Kondo effect is an important issue in condensed-matter physics [1] and has been attracted extensive attention since its first discovery, because the Kondo effect could provide a deeper understanding of the physical properties of many strong correlated systems [2]. On the other hand, a quasi-zero-dimensional system called quantum dot (QD), of which the parameters can be modulated experimentally in a continuous and reproducible manner, offers proper platform to study the Kondo problems [3, 4, 5, 6, 7]. Under appropriate conditions, the Kondo effect can arise from the coherent superposition of the cotunneling processes [2, 6], where the spin degree of freedom plays a significant role and the electron in the QD can flip its spin. At low temperature, the coherent superposition of many cotunneling processes could lead to the Kondo resonant state in which the spin flip occurs frequently within the QD and a very sharp Kondo peak emerges in the density of state of the QD.

Later on, the Kondo effect was proposed based on the orbital degree of freedom [8, 9, 10, 11, 12, 13, 14]. It was reported that double QD (DQD) could become a good candidate for realizing the orbital Kondo effect [8, 14, 15, 16, 17, 18, 19, 20, 21]. In this situation, the energy of the orbital state in the left QD can be the same as or very close to that in the right QD. Then, the corresponding left and right orbital states are degenerate or near degenerate, and they can be regarded as pseudospin degenerate states [8, 22, 23]. In real spin systems, it is difficult to manipulate the spin-up state and the spin-down one individually. In contrast, since the left and right QDs of the DQD system are separated in space, it is much easier to control over both QDs and each of them can be seen as a pseudospin component [14, 18, 24, 25, 26, 27]. As a result, the physical phenomenon, which is related to the spin degree of freedom, may also be realized in the DQD system including the pseudospin (orbital) degree of freedom.

Very recently, the pseudospin-resolved transport spectroscopy of the Kondo effect has been observed in a DQD device on the basis of a orbital degeneracy [14]. The schematic diagram of this device is shown in figure 1(a). In the experiment, the authors fabricated the parallel DQD system from an epitaxially grown AlGaAs/GaAs heterostructure. As illustrated in figure 1(a), Q_L and Q_R are the parallel QDs, which are capacitively coupled with each other. The voltages applied on the gates P_L and P_R are used to control the occupancy of the dots. The gates W_{LS} (W_{RS}) and W_{LD} (W_{RD}) control the tunneling rates between dot Q_L (Q_R) and its source lead LS (RS) and drain lead LD (RD). The gates C_S and C_D are used to control the interdot tunneling. In [14], the authors applied negative voltages on the gates C_S and C_D to make the interdot tunneling negligible. They measured the standard transport spectroscopy as a function of the bias voltages and observed a zero-bias peak in the conductance. Furthermore, if the orbital degeneracy is broken, the Kondo resonances have different pseudospin character. Using pseudospin-resolved spectroscopy, they observed a Kondo peak at only one sign of the bias voltage.

In this paper, we theoretically investigate the orbital Kondo effect in a parallel

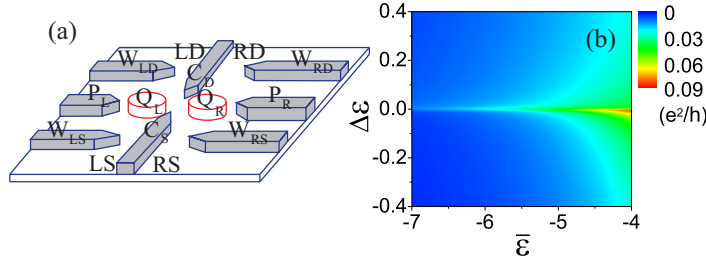


Figure 1. (a) Schematic diagram for a parallel DQD device. Q_L and Q_R are the left and right QDs. The gates P_L and P_R are used to control the occupancy of the QDs. The tunneling rates between dot Q_L (Q_R) and its source lead LS (RS) and drain lead LD (RD) are controlled by gates W_{LS} (W_{RS}) and W_{LD} (W_{RD}), respectively. The gates C_S and C_D are used to control the interdot tunneling. (b) G_{LS} as functions of $\bar{\epsilon}$ and $\Delta\epsilon$. The source and drain voltages are $V_{LS} = V_{RS} = V_{LD} = V_{RD} = 0$. Here, the temperature keeps $T = 0.001$ and $t_c = 0$.

DQD. It need to mention that the properties of DQDs have been studied by lots of theoretical works [15, 16, 17, 18, 19]. In this work, by using the non-equilibrium Green's function method and the equation of motion technique, the formula of the conductance for each pseudospin component and the pseudospin flipping current are obtained. The main new results are listed as follows: (1) If the interdot tunneling coupling t_c is zero, we reproduce the experimental results in [14], where two Kondo peaks were observed in the conductance-bias curve for the pseudospin-non-resolved case and only one Kondo peak was found in the pseudospin-resolved case. In the curve of the conductance versus the pseudospin splitting energy, there exist three and two Kondo peaks for the pseudospin-non-resolved and pseudospin-resolved cases, respectively. (2) When the interdot tunneling coupling t_c is nonzero, the levels in the DQD can form molecular states. Then, the Kondo peaks can emerge at $\Delta E = \pm V_{LS}$ for both pseudospin-non-resolved and pseudospin-resolved cases, where ΔE is the energy difference between the two molecular states and V_{LS} is the lead voltage. Besides, an additional Kondo peak and dip structure could emerge at $\Delta E = 0$. (3) The pseudospin transport and the pseudospin flipping current in the DQD system are studied. In particular, the pseudospin system is much easier to be controlled and measured than the real spin current, so the pseudospin DQD system can be a good candidate for studying the properties related to the spin degree of freedom.

The rest of the paper is organized as follows. In section 1.1, we propose the model Hamiltonian, and use the non-equilibrium Green's function method to get the current and conductance formulas. In section 2, we numerically investigate the conductances and the pseudospin flipping current of the DQD in different cases. Finally, we give the conclusions in section 3.

1.1. Model and analytical results

The Hamiltonian of the DQD system as shown in figure 1(a) can be written as

$$H = H_{DQD} + H_T + \sum_{\alpha\beta} H_{\alpha\beta}, \quad (1)$$

where

$$\begin{aligned} H_{DQD} &= \sum_{\alpha} \varepsilon_{\alpha} d_{\alpha}^{\dagger} d_{\alpha} + U d_L^{\dagger} d_L d_R^{\dagger} d_R + (t_c d_L^{\dagger} d_R + h.c.), \\ H_T &= \sum_{\alpha\beta k} (t_{\alpha\beta} a_{\alpha\beta k}^{\dagger} d_{\alpha} + h.c.), \\ H_{\alpha\beta} &= \sum_k \varepsilon_{\alpha\beta k} a_{\alpha\beta k}^{\dagger} a_{\alpha\beta k}. \end{aligned}$$

Here, H_{DQD} is the Hamiltonian of the DQD and d_{α}^{\dagger} (d_{α}) is the creation (annihilation) operator of the electron in the QDs with $\alpha = L/R$ representing left and right. ε_{α} is the energy level of the QDs, U is the interdot electron-electron interaction, and t_c is the tunneling coupling. H_T denotes the tunneling between the DQD and the leads. $a_{\alpha\beta k}^{\dagger}$ ($a_{\alpha\beta k}$) is the creation (annihilation) operator of the electron in the leads, with $\beta = S/D$ being source and drain. $H_{\alpha\beta}$ describes the noninteracting leads. It should be noted that when a high magnetic field is applied to the QD, the spin splitting energy can be comparable with or even larger than the QD energy level spacing [8, 28, 29]. Then, as compared with the low energy spin state, the opposite spin state does not affect the transport property of the system at low bias. Thus, we can neglect the spin degree of freedom. Meanwhile, we consider the low bias case with its value being less than the intradot electron-electron interaction energy U_0 . In this case, there is only one eigenstate in each QD in the bias window. Then, we can absorb the intradot interaction U_0 into the energy levels ε_L and ε_R [8, 30]. As a result, both the spin degree of freedom and the intradot interaction can be ignored, leaving only the interdot interaction U . This approximation has been adopted in [8, 30].

This model can describe various properties of the parallel DQD, including the properties illustrated in the recent experiment of [14], and could also be used to study the pseudospin transport. Here, we briefly introduce the concept of the pseudospin transport in the parallel DQD. As we know, the electron has two spin states: spin up and spin down. The transport related to spin is called spin transport. Similarly, the electron in the DQD also has two states: the electron in the left QD and that in the right QD. When the electron is in the left (right) QD, we can call it the pseudospin up (down) state. The transport related to the pseudospin is called the pseudospin transport. There are four advantages of the pseudospin transport: (1) The electrons with different spins have the same chemical potential in the wires, i.e., $\mu_{\uparrow} = \mu_{\downarrow}$. Thus, it is difficult to manipulate the electrons with specific spin while keeping the other spin unchanged. Even if we can achieve the case of $\mu_{\uparrow} \neq \mu_{\downarrow}$ by some special methods [31, 32], the spin voltage $\mu_{\uparrow} - \mu_{\downarrow}$ is still difficult to control. While regarding the pseudospin, however, the situation is totally different. The voltages applied on the wires connected to the left and right QDs can be manipulated separately. This means that the chemical potentials of

the electrons with different pseudospins, μ_L and μ_R , can be easily controlled, which has been realized in the experiment [14]. (2) Since the energy levels of different QDs can be manipulated by the gates P_L and P_R , the pseudospin splitting energy $\Delta\varepsilon = \varepsilon_L - \varepsilon_R$ can be adjusted in a wide range. (3) The pseudospin flipping strength t_c in the DQD can also be tuned by the gates C_D and C_S . It can be open or closed by simply tuning the gate voltages. (4) The real spin in the lead is difficult to keep its direction and the spin flipping exists inevitably. Contrarily, the pseudospin can keep its “direction” steadily outside the DQD because the electrons in the left lead cannot tunnel into the right lead and vice versa. So the pseudospin flipping current in the DQD can accurately be measured in the experiment.

Next, we will use the standard equation of motion technique to solve the retarded Green’s function [8, 33, 34, 35]. The equation of motion is:

$$\varepsilon \langle \langle A|B \rangle \rangle^r = \langle \{ \hat{A}, \hat{B} \} \rangle + \langle \langle [\hat{A}, H] | \hat{B} \rangle \rangle^r, \quad (2)$$

where \hat{A} and \hat{B} are arbitrary operators, and $\langle \langle A|B \rangle \rangle^r$ is the standard notation of the retarded Green’s function. Since higher order Green’s functions will appear in the calculations of equation of motion, a decoupling schemes is needed. The decoupling scheme in this work takes the following rules: (1) if we use X to represent the leads operator ($a_{\alpha\beta k}$ and $a_{\alpha\beta k}^\dagger$) and use Y to represent the DQDs operator (d_α and d_α^\dagger), then we take $\langle XY \rangle = 0$. (2) If the two-particle Green’s function involves two leads operators, then we take $\langle \langle X_1 X_2 Y | d_\alpha^\dagger \rangle \rangle^r = \langle X_1 X_2 \rangle \langle \langle Y | d_\alpha^\dagger \rangle \rangle^r$. (3) If the two-particle Green’s function involves only one leads operator, which is $\langle \langle X Y_1 Y_2 | d_\alpha^\dagger \rangle \rangle^r$, we continue to apply the equation of motion until all the two-particle Green’s functions contain two leads operators. This decoupling scheme has been used in previous papers [8, 33].

Moreover, because the method of derivation we used are similar to Ref. [8], we omit the detailed derivation and only show the results in this paper. It should be pointed out that although we use the same calculation method with Ref. [8], the research subject and conclusions are totally different. Ref. [8] described the series DQDs, while the present work refers to the parallel DQDs. Unlike the series DQDs in Ref. [8], the conductance can hold a pseudospin-resolved character in the parallel DQDs system when the interdot tunnelling $t_c = 0$. The pseudospin transport and the pseudospin flipping current can also be studied in the present model while $t_c \neq 0$, and the calculation presents a new method to measure and control the pseudospin transport in the parallel DQDs system.

In addition, it is worth mentioning that although the equation of motion method based on non-equilibrium Green’s function cannot quantitatively obtain the intensity of the Kondo effect, it can give the qualitative physics and the positions of the Kondo peaks. Using the equation of motion in equation (2), we can obtain the matrix equation:

$$\begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix} \cdot \begin{pmatrix} \langle \langle d_L | d_L^\dagger \rangle \rangle^r & \langle \langle d_L | d_R^\dagger \rangle \rangle^r \\ \langle \langle d_R | d_L^\dagger \rangle \rangle^r & \langle \langle d_R | d_R^\dagger \rangle \rangle^r \end{pmatrix} = \begin{pmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{pmatrix}, \quad (3)$$

where

$$C_{11} = \varepsilon - \varepsilon_L - \Sigma_{LS}^0 - \Sigma_{LD}^0 + U A_L B \left(\tilde{t}_c A_R \Sigma^d \right)$$

$$\begin{aligned}
& +\Sigma_{RS}^a + \Sigma_{RD}^a + \Sigma_{RS}^b + \Sigma_{RD}^b + \Sigma_{LS}^c + \Sigma_{LD}^c), \\
C_{12} = & -t_c + UA_L B \left[\tilde{t}_c A_R (\Sigma_{LS}^a + \Sigma_{LD}^a + \Sigma_{LS}^b \right. \\
& \left. + \Sigma_{LD}^b + \Sigma_{RS}^c + \Sigma_{RD}^c) + \Sigma^d \right], \\
C_{21} = & -t_c + UA_R B \left[\tilde{t}_c A_L (\Sigma_{RS}^a + \Sigma_{RD}^a + \Sigma_{RS}^b \right. \\
& \left. + \Sigma_{RD}^b + \Sigma_{LS}^c + \Sigma_{LD}^c) + \Sigma^d \right], \\
C_{22} = & \varepsilon - \varepsilon_R - \Sigma_{RS}^0 - \Sigma_{RD}^0 + UA_R B \left(\tilde{t}_c A_L \Sigma^d \right. \\
& \left. + \Sigma_{LS}^a + \Sigma_{LD}^a + \Sigma_{LS}^b + \Sigma_{LD}^b + \Sigma_{RS}^c + \Sigma_{RD}^c \right), \\
D_{11} = & 1 + UA_L B n_R - UA_L B \tilde{t}_c A_R \langle d_L^\dagger d_R \rangle, \\
D_{12} = & -UA_L B \langle d_R^\dagger d_L \rangle + UA_L B \tilde{t}_c A_R n_L, \\
D_{21} = & -UA_R B \langle d_L^\dagger d_R \rangle + UA_R B \tilde{t}_c A_L n_R, \\
D_{22} = & 1 + UA_R B n_L - UA_R B \tilde{t}_c A_L \langle d_R^\dagger d_L \rangle.
\end{aligned}$$

The expressions of the above notations are listed as follows:

$$\begin{aligned}
\Sigma_{\alpha\beta}^0 &= \sum_k \frac{|t_{\alpha\beta}|^2}{\varepsilon - \varepsilon_{\alpha\beta k}} = -\frac{i}{2} \Gamma_{\alpha\beta}, \\
\tilde{\varepsilon}_{\alpha\beta k}^2 &= (\varepsilon + \varepsilon_L - \varepsilon_R - \varepsilon_{\alpha\beta k})(\varepsilon - \varepsilon_L + \varepsilon_R - \varepsilon_{\alpha\beta k}) - 4t_c^2, \\
\Sigma_{\alpha\beta}^{1/a} &= \sum_k \frac{|t_{\alpha\beta}|^2}{\varepsilon - \varepsilon_L - \varepsilon_R + \varepsilon_{\alpha\beta k} - U} F_{\alpha\beta}^{1/a}(\varepsilon_{\alpha\beta k}), \\
\Sigma_{\alpha\beta}^{2/b} &= \sum_k \frac{(\varepsilon - \varepsilon_{\alpha\beta k})(\varepsilon - \varepsilon_\alpha + \varepsilon_{\bar{\alpha}} - \varepsilon_{\alpha\beta k}) - 2t_c^2}{(\varepsilon - \varepsilon_{\alpha\beta k})\tilde{\varepsilon}_{\alpha\beta k}^2} \cdot |t_{\alpha\beta}|^2 F_{\alpha\beta}^{1/a}(\varepsilon_{\alpha\beta k}), \\
\Sigma_{\alpha\beta}^{3/c} &= \sum_k \frac{2t_c^2}{(\varepsilon - \varepsilon_{\alpha\beta k})\tilde{\varepsilon}_{\alpha\beta k}^2} |t_{\alpha\beta}|^2 F_{\alpha\beta}^{1/a}(\varepsilon_{\alpha\beta k}), \\
\Sigma_{\alpha\beta}^{4/d} &= \sum_k \frac{\varepsilon - \varepsilon_\alpha + \varepsilon_{\bar{\alpha}} - \varepsilon_{\alpha\beta k}}{(\varepsilon - \varepsilon_{\alpha\beta k})\tilde{\varepsilon}_{\alpha\beta k}^2} t_c |t_{\alpha\beta}|^2 F_{\alpha\beta}^{1/a}(\varepsilon_{\alpha\beta k}), \\
A_\alpha^{-1} &= \varepsilon - \varepsilon_\alpha - U - \Sigma_{\alpha S}^0 - \Sigma_{\alpha D}^0 - \Sigma_{\bar{\alpha} S}^1 - \Sigma_{\bar{\alpha} D}^1 \\
& \quad - \Sigma_{\bar{\alpha} S}^2 - \Sigma_{\bar{\alpha} D}^2 - \Sigma_{\alpha S}^3 - \Sigma_{\alpha D}^3, \\
\Sigma^d &= \Sigma_{LS}^d + \Sigma_{LD}^d + \Sigma_{RS}^d + \Sigma_{RD}^d, \\
\tilde{t}_c &= t_c + \Sigma_{LS}^4 + \Sigma_{LD}^4 + \Sigma_{RS}^4 + \Sigma_{RD}^4, \\
B^{-1} &= 1 - \tilde{t}_c^2 A_L A_R.
\end{aligned}$$

In the above equations, $F_{\alpha\beta}^1(\varepsilon_{\alpha\beta k}) = 1$ and $F_{\alpha\beta}^a(\varepsilon_{\alpha\beta k}) = f_{\alpha\beta}(\varepsilon_{\alpha\beta k})$, where $f_{\alpha\beta}(\varepsilon_{\alpha\beta k}) = 1/\{\exp[(\varepsilon_{\alpha\beta k} - \mu_{\alpha\beta})/k_B T] + 1\}$ is the Fermi distribution function and $\mu_{\alpha\beta} = eV_{\alpha\beta}$ is the chemical potential of the lead $\alpha\beta$. α and $\bar{\alpha}$ denote different left-right positions. That is, if α is left, $\bar{\alpha}$ is right; if α is right, $\bar{\alpha}$ is left. $\Sigma_{\alpha\beta}^1$, $\Sigma_{\alpha\beta}^2$, $\Sigma_{\alpha\beta}^3$, $\Sigma_{\alpha\beta}^4$, $\Sigma_{\alpha\beta}^a$, $\Sigma_{\alpha\beta}^b$, $\Sigma_{\alpha\beta}^c$, and $\Sigma_{\alpha\beta}^d$ are the higher-order self-energies.

Taking the limit of $U \rightarrow \infty$, equation (3) can be simplified and the elements of the matrices are replaced by:

$$C_{11} = \varepsilon - \varepsilon_L - \Sigma_{LS}^0 - \Sigma_{LD}^0 - \Sigma_{RS}^b - \Sigma_{RD}^b - \Sigma_{LS}^c - \Sigma_{LD}^c,$$

$$\begin{aligned}
C_{12} &= -t_c - \Sigma^d, \\
C_{21} &= -t_c - \Sigma^d, \\
C_{22} &= \varepsilon - \varepsilon_R - \Sigma_{RS}^0 - \Sigma_{RD}^0 - \Sigma_{LS}^b - \Sigma_{LD}^b - \Sigma_{RS}^c - \Sigma_{RD}^c,
\end{aligned}$$

and $D_{11} = 1 - n_R$, $D_{12} = \langle d_R^\dagger d_L \rangle$, $D_{21} = \langle d_L^\dagger d_R \rangle$, and $D_{22} = 1 - n_L$.

By using the non-equilibrium Green's function, the current from the lead $\alpha\beta$ flowing into the system can be obtained as [8]:

$$J_{\alpha\beta} = -\frac{e}{\pi} \Gamma_{\alpha\beta} \int d\varepsilon f_{\alpha\beta}(\varepsilon) \text{Im} G_{\alpha\alpha}^r - e \Gamma_{\alpha\beta} \langle d_\alpha^\dagger d_\alpha \rangle \quad (4)$$

In the expressions of the current and the coefficients D_{ij} , $\langle d_\alpha^\dagger d_{\alpha'} \rangle$ is determined self-consistently. From the relation $\langle d_\alpha^\dagger d_{\alpha'} \rangle = -i \int (d\varepsilon/2\pi) G_{\alpha\alpha'}^<(\varepsilon)$ with the lesser Green's function $G_{\alpha\alpha'}^<(\varepsilon)$, the self-consistent equations can exactly be derived [8]:

$$\begin{aligned}
& -t_c \langle d_R^\dagger d_L \rangle + t_c \langle d_L^\dagger d_R \rangle - i \Gamma_{LS} \langle d_L^\dagger d_L \rangle - i \Gamma_{LD} \langle d_L^\dagger d_L \rangle \\
& = \int \frac{d\varepsilon}{2\pi} (\Gamma_{LS} f_{LS} + \Gamma_{LD} f_{LD}) (G_{LL}^r - G_{LL}^a), \quad (5)
\end{aligned}$$

$$\begin{aligned}
& (-\varepsilon_L + \varepsilon_R - \frac{i}{2} \Gamma_{LS} - \frac{i}{2} \Gamma_{LD} - \frac{i}{2} \Gamma_{RS} \\
& - \frac{i}{2} \Gamma_{RD}) \langle d_L^\dagger d_R \rangle + t_c \langle d_L^\dagger d_L \rangle - t_c \langle d_R^\dagger d_R \rangle \\
& = \int \frac{d\varepsilon}{2\pi} (\Gamma_{LS} f_{LS} + \Gamma_{LD} f_{LD}) G_{RL}^r - \int \frac{d\varepsilon}{2\pi} (\Gamma_{RS} f_{RS} + \Gamma_{RD} f_{RD}) G_{RL}^a, \quad (6)
\end{aligned}$$

$$\begin{aligned}
& -t_c \langle d_L^\dagger d_R \rangle + t_c \langle d_R^\dagger d_L \rangle - i \Gamma_{RS} \langle d_R^\dagger d_R \rangle - i \Gamma_{RD} \langle d_R^\dagger d_R \rangle \\
& = \int \frac{d\varepsilon}{2\pi} (\Gamma_{RS} f_{RS} + \Gamma_{RD} f_{RD}) (G_{RR}^r - G_{RR}^a), \quad (7)
\end{aligned}$$

$$\begin{aligned}
& (\varepsilon_L - \varepsilon_R - \frac{i}{2} \Gamma_{LS} - \frac{i}{2} \Gamma_{LD} - \frac{i}{2} \Gamma_{RS} \\
& - \frac{i}{2} \Gamma_{RD}) \langle d_R^\dagger d_L \rangle + t_c \langle d_R^\dagger d_R \rangle - t_c \langle d_L^\dagger d_L \rangle \\
& = \int \frac{d\varepsilon}{2\pi} (\Gamma_{RS} f_{RS} + \Gamma_{RD} f_{RD}) G_{LR}^r - \int \frac{d\varepsilon}{2\pi} (\Gamma_{LS} f_{LS} + \Gamma_{LD} f_{LD}) G_{LR}^a. \quad (8)
\end{aligned}$$

If we substitute the initial values of $\langle d_L^\dagger d_L \rangle$, $\langle d_L^\dagger d_R \rangle$, $\langle d_R^\dagger d_L \rangle$, and $\langle d_R^\dagger d_R \rangle$ into equations (5)-(8), and solve them self-consistently, we can get the convergent values of them. Then substituting $\langle d_L^\dagger d_L \rangle$, $\langle d_R^\dagger d_R \rangle$, and the Green's function of equation (3) into equation (4), we can get the current. Besides, the conductance can also be calculated. During the process of calculations, there is one thing should be emphasized. In general, the lesser Green's function $G^<(\varepsilon)$ can not be solved exactly for interacting systems. However, in our calculations, we do not have to solve $G^<(\varepsilon)$ itself. When we calculate the self-consistent equations and the electric current, the quantity we actually need is $\int d\varepsilon G^<(\varepsilon)$ rather than $G^<(\varepsilon)$. Because $\int d\varepsilon G^<(\varepsilon)$ can be solve exactly in our model, we need not any approximation involved in computing $\int dG^<(\varepsilon)$ [8].

As we know, the conductance of the two-terminal system is defined as $G = \frac{dI}{dV}$. While in the DQD system, there are four wires, i.e., four terminals, and we can define $4 \times 4 = 16$ conductances in principle. In the following, we define the conductance as:

$$G_{\alpha\beta}(V_{\alpha\beta}, V_{\alpha\bar{\beta}}, V_{\bar{\alpha}\beta}, V_{\bar{\alpha}\bar{\beta}}) = \lim_{V \rightarrow 0} \frac{[I_{\alpha\beta}(V_{\alpha\beta} + \frac{V}{2}, V_{\alpha\bar{\beta}} - \frac{V}{2}, V_{\bar{\alpha}\beta}, V_{\bar{\alpha}\bar{\beta}}) - I_{\alpha\beta}(V_{\alpha\beta}, V_{\alpha\bar{\beta}}, V_{\bar{\alpha}\beta}, V_{\bar{\alpha}\bar{\beta}})]}{V}, \quad (9)$$

where β and $\bar{\beta}$ denote different source-drain leads. This definition of the conductance is the quantity measured in the recent experiment [14]. Here, we mainly focus on two different ways of the applied external voltages in the numerical calculations. One is keeping $V_{LD} = V_{RD} = 0$, $V_{LS} = V_{RS}$, and changing V_{LS} and V_{RS} simultaneously. The other is keeping $V_{RS} = V_{LD} = V_{RD} = 0$, and changing V_{LS} alone. The former way changes the chemical potentials of both pseudospin up electron and pseudospin down one simultaneously, which is similar to the experiments related to the real spin because the chemical potentials of the spin up electron and the spin down one are difficult to change separately. Therefore, we could get the pseudospin-non-resolved results in this way. The latter way changes the chemical potential of the pseudospin up electron only, thus we can obtain the pseudospin-resolved results, which is the key point in [14]. We will compare these two ways carefully under different external conditions in this paper.

2. Numerical results and analysis

In this section, we at first discuss the case of negligible interdot tunneling, then generalize our study to the case of finite interdot tunneling, and at last study the pseudospin flipping current in the DQD. In our calculations, we have taken $\Gamma_{LS} = \Gamma_{LD} = \Gamma_{RS} = \Gamma_{RD} = 1$ in all cases.

2.1. The numerical results without interdot tunneling

In this subsection, we focus on the case without any interdot tunneling. Before we discuss the conductance of the DQD, there is one thing to be emphasized. When the interdot tunneling is ignored, i.e., $t_c = 0$, there is no pseudospin flipping and we could get the results of $G_{LS} = G_{LD}$ and $G_{RS} = G_{RD}$. When finite interdot tunneling exists, i.e., $t_c \neq 0$, all of the four conductances may not be the same, which is determined by the structure of the DQD's energy levels and voltages. In addition, since the characters of the four conductances are similar, we only analyse G_{LS} . Figure 1(b) shows the conductance G_{LS} as functions of $\bar{\varepsilon}$ and $\Delta\varepsilon$, where $\bar{\varepsilon} = \frac{\varepsilon_L + \varepsilon_R}{2}$ and $\Delta\varepsilon = \varepsilon_L - \varepsilon_R$. The different color represents different values of the conductance. We can see a bright peak emerging at $\Delta\varepsilon = 0$, which is the zero-bias Kondo resonant peak.

Next we study the conductance in detail. Figures 2(a) and 2(b) show G_{LS} as a function of the bias voltage V_{LS} , while figures 2(c) and 2(d) illustrate G_{LS} as a function of the pseudospin splitting energy $\Delta\varepsilon$. In figure 2(a), we keep $V_{LS} = V_{RS}$ and $V_{LD} = V_{RD} = 0$, implying that the chemical potentials of both pseudospin up and down electrons are changed simultaneously. When $\Delta\varepsilon = 0$, the Kondo peak emerges

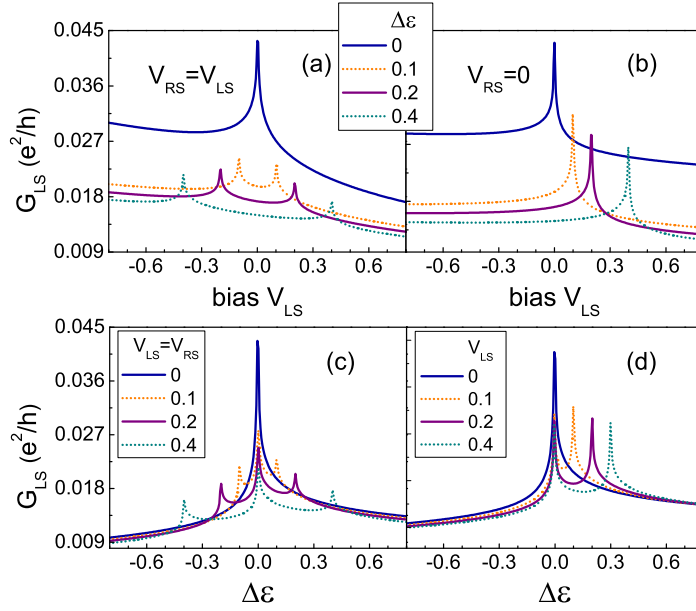


Figure 2. (a) and (b) G_{LS} as a function of V_{LS} at different $\Delta\epsilon$. (c) and (d) G_{LS} as a function of $\Delta\epsilon$ at different V_{LS} . In (a) and (c), the voltages V_{LS} and V_{RS} are changed simultaneously, with $V_{LS} = V_{RS}$ and $V_{LD} = V_{RD} = 0$. In (b) and (d), only V_{LS} is changed, with $V_{RS} = V_{LD} = V_{RD} = 0$. Other parameters are $T = 0.001$, $\bar{\epsilon} = -5.0$, and $t_c = 0$.

at $V_{LS} = 0$; when $\Delta\epsilon \neq 0$, the Kondo peak splits into two peaks at $V_{LS} = \pm\Delta\epsilon$. This phenomenon is similar to the splitting of the spin Kondo peak of a single QD in the magnetic field, and $\Delta\epsilon$ is equivalent to the Zeeman energy due to the magnetic field. This is the pseudospin-non-resolved Kondo effect. In figure 2(b), we keep $V_{RS} = V_{LD} = V_{RD} = 0$ and change V_{LS} only. Since the chemical potential of the pseudospin up electron in the source wire is changed only, there is a single peak emerging at $V_{LS} = \Delta\epsilon$. This is the pseudospin-resolved effect. The results in figures 2(a) and 2(b) are in good agreement with the recent experiment [14].

Next we discuss the relation between the conductance G_{LS} and the pseudospin splitting energy $\Delta\epsilon$ which is shown in figures 2(c) and 2(d). In figure 2(c), we keep $V_{LD} = V_{RD} = 0$ and $V_{LS} = V_{RS}$. If $V_{LS} = V_{RS} = 0$, there exists only one Kondo peak which locates at $\Delta\epsilon = 0$. This is well-known in the spin Kondo system. While $V_{LS} = V_{RS} \neq 0$, the Kondo peak is divided into three peaks with their positions locating at $\Delta\epsilon = 0, \pm V_{LS}$. In figure 2(d), we keep $V_{RS} = V_{LD} = V_{RD} = 0$ and change V_{LS} alone. Different from figure 2(c), only two peaks are found at $\Delta\epsilon = 0, V_{LS}$ in figure 2(d) when $V_{LS} \neq 0$, and the original peak at $\Delta\epsilon = -V_{LS}$ disappear because the chemical potential of the pseudospin down electron in the source wire is zero exactly. It should be noted that since the spin-up and spin-down chemical potentials in the real spin system are difficult to manipulate separately, it is not easy to observe these phenomena as shown in figures 2(c) and 2(d). However, these phenomena are easy to be observed in the parallel DQD system because it is easy to manipulate the chemical potentials and the splitting

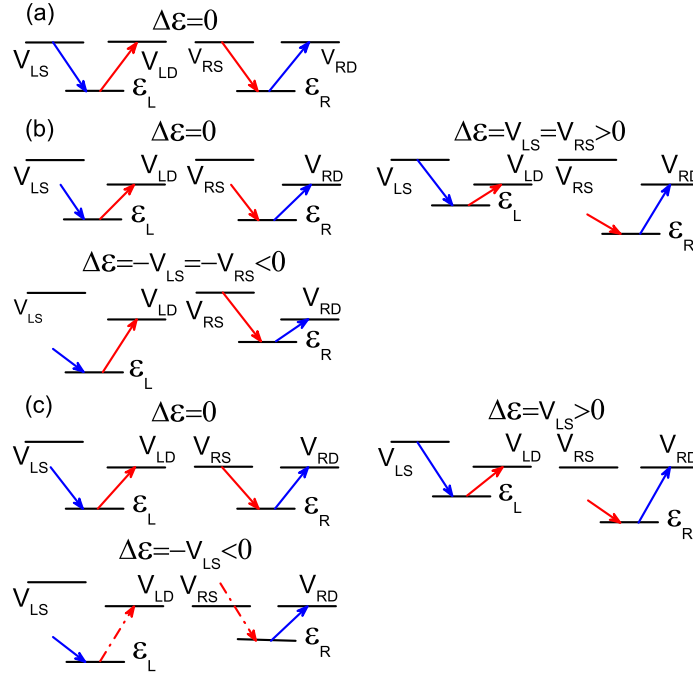


Figure 3. Schematic diagram of the electron cotunneling processes between the DQD and the leads. (a) shows the case when $V_{LS} = V_{RS} = V_{LD} = V_{RD} = 0$ and $\Delta\epsilon = 0$. In (a), an electron tunnels from the right QD into the lead RD and another electron tunnels from the lead LS into the left QD, which is shown by the blue arrows. The red arrows show two similar tunneling events: an electron tunnels from the left QD to the lead LD and another one tunnels from the lead RS into the right QD. By combining these four events, the electrons can pass through both QDs. (b) shows the similar cotunneling processes when $V_{LD} = V_{RD} = 0$ and $V_{LS} = V_{RS} \neq 0$. (c) shows the similar cotunneling processes when $V_{RS} = V_{LD} = V_{RD} = 0$ and $V_{LS} \neq 0$. Both (b) and (c) illustrate three different cases: $\Delta\epsilon = 0$, $\Delta\epsilon > 0$, and $\Delta\epsilon < 0$. The dash-dotted lines in (c) indicate that the tunneling events are forbidden.

of the pseudospin degree of freedom.

The Kondo peaks in figure 2 can be understood by the cotunneling processes shown in figure 3. It should be pointed out that the Kondo effect can be captured by the fourth or higher-order perturbation processes with respect to the tunneling between dot and leads. As we can see from figure 3, when the electric state in the parallel DQDs returns to its original state, it has experienced four tunneling processes (shown by two red lines and two blue lines). These four tunneling processes make up two cotunneling processes, and each cotunneling process is a second order perturbation process. Notice that Only the combination of two cotunneling processes can lead to the Kondo effect. The similar explanation, which interprets the Kondo effect by cotunneling precesses, has been used in many previous papers [8, 15, 36, 37, 38]. Figure 3(a) plots a cotunneling process which leads to the main Kondo resonance when $V_{LS} = V_{LD} = V_{RS} = V_{RD} = 0$ and $\Delta\epsilon = 0$ (blue lines in figures 2(c) and 2(d)). The blue and red arrows illustrate the correlative tunneling events, respectively. To be specific, we first consider an electron in the right QD. This electron can tunnel from the right QD into the lead RD . Then,

another electron in the lead LS with the energy V_{RD} can tunnel into the left QD. These two tunneling events are shown by the blue arrows. After that, the left QD is occupied and the right QD is empty, where the system energy is the same as that in the beginning state. The red arrows show another two similar tunneling events, where an electron in the left QD tunnels into the lead LD and then another electron in the lead RS tunnels into the right QD. With the above four tunneling events, although the system recovers to the beginning state, the electrons travel from the left (right) source lead through the left (right) QD to the left (right) drain lead. When many of these cotunneling processes take coherent superposition at low temperature, a Kondo resonance will appear. This leads to the main Kondo peak at $\Delta\varepsilon = 0$ in figure 2(c) for $V_{LS} = V_{RS} = 0$ and in figure 2(d) for $V_{LS} = 0$. Figure 3(b) explains the emergence of three peaks when $V_{LS} = V_{RS} \neq 0$ in figure 2(c). No matter $\Delta\varepsilon = 0$, $\Delta\varepsilon > 0$, or $\Delta\varepsilon < 0$, the electrons can travel through both QDs because of the cotunneling processes shown in figure 3(b), and thus three peaks appear in figure 2(c). On the other hand, it should be pointed out that the energy is conserved in the cotunneling processes. Therefore, for $\Delta\varepsilon = 0$ in figure 3(b), when an electron in the right QD tunnels into the lead RD , another electron in the lead LS with the energy V_{RD} can tunnel into the left QD. For $\Delta\varepsilon > 0$ ($\Delta\varepsilon < 0$), the condition of $V_{LS} - \varepsilon_L = V_{RD} - \varepsilon_R$ ($V_{LD} - \varepsilon_L = V_{RS} - \varepsilon_R$) should be preserved due to the energy conservation in the cotunneling processes. Since we keep $V_{LD} = V_{RD} = 0$ and $V_{LS} = V_{RS}$, the Kondo peaks can emerge at $\Delta\varepsilon \equiv \varepsilon_L - \varepsilon_R = \pm V_{LS} = \pm V_{RS}$ (see figure 2(c)). Figure 3(c) explains the emergence of two peaks when $V_{LS} \neq 0$ in figure 2(d). For $\Delta\varepsilon = 0$ and $\Delta\varepsilon > 0$, the electrons can pass through both QDs. However, for $\Delta\varepsilon < 0$, the energy obtained from the electron jumping from the right source lead RS to the right QD cannot support the tunneling event from the left QD to the drain lead LD (shown by the red dash-dotted lines). Therefore, the electrons cannot travel through the DQD for $\Delta\varepsilon < 0$. As a result, no Kondo peak appears at $\Delta\varepsilon = -V_{LS}$ and there are only two Kondo peaks at $\Delta\varepsilon = 0$ and $\Delta\varepsilon = V_{LS}$ in figure 2(d).

In general, if the four lead voltages V_{LS} , V_{LD} , V_{RS} , and V_{RD} do not equal to each other, there are four Kondo peaks with their positions at $\Delta\varepsilon = V_{LS} - V_{RS}$, $\Delta\varepsilon = V_{LS} - V_{RD}$, $\Delta\varepsilon = V_{LD} - V_{RS}$, and $\Delta\varepsilon = V_{LD} - V_{RD}$, respectively. It should be noted that although it can have four Kondo peaks in the curve of the conductance as a function of the pseudospin splitting $\Delta\varepsilon$, there are at most two Kondo peaks in the curve of the conductance versus the voltage, e.g., G_{LS} versus V_{LS} . When some of the four lead voltages have identical value, some Kondo peaks will overlap and then the number of the peaks can be reduced, as shown in figure 2. Figure 4(a) displays G_{LS} versus $\Delta\varepsilon$ with $V_{LS} = 0.3$, $V_{RS} = 0.2$, and $V_{LD} = V_{RD} = 0$, in which four Kondo peaks clearly exhibit. Figure 4(b) shows G_{LS} versus the voltage V_{LS} by fixing $V_{RS} = 0.2$, $V_{LD} = 0$, and $V_{RD} = -0.1$ with different pseudospin splitting energy $\Delta\varepsilon$. Here, two Kondo peaks emerge. It is worth mentioning that the conductance G_{LS} at $\Delta\varepsilon = -0.2$ is obviously larger than the other cases. This is due to the fact that when $\Delta\varepsilon = -0.2$, $\Delta\varepsilon = V_{LD} - V_{RS}$ keeps, regardless of the voltage V_{LS} . This means that the Kondo resonance occurs always, so a very large conductance G_{LS} could be observed at low

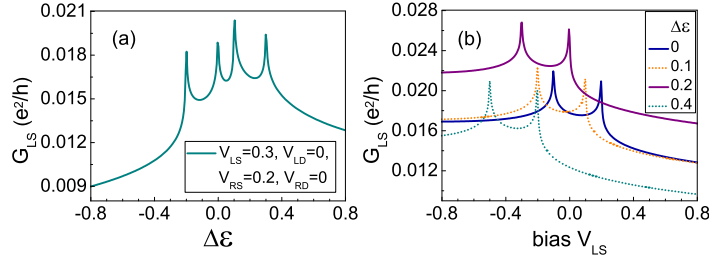


Figure 4. (a) Conductance G_{LS} as a function of the pseudospin splitting energy $\Delta\epsilon$ with $V_{LS} = 0.3$, $V_{RS} = 0.2$, and $V_{LD} = V_{RD} = 0$. (b) G_{LS} versus the voltage V_{LS} at different $\Delta\epsilon$ with $V_{RS} = 0.2$, $V_{LD} = 0.0$, and $V_{RD} = -0.1$. The remaining parameters are $T = 0.001$, $\bar{\epsilon} = -5.0$, and $t_c = 0$.

temperature.

2.2. The effect of the interdot tunneling

When the interdot tunneling coupling t_c is considered, we can generalize the experimental results of [14]. Before the discussion of the conductance, let us first analyse the cotunneling processes at $t_c \neq 0$. Figure 5(d) shows the change of the energy level of the DQD in the presence of t_c . When $t_c \neq 0$, the energy levels in the left and right QDs will hybridize into the molecular states. That is, ϵ_L and ϵ_R can be recombined into $\epsilon^\pm = \frac{(\epsilon_L + \epsilon_R)}{2} \pm \frac{\Delta E}{2}$ which expands to the entire device at $\Delta\epsilon = 0$ [8, 39, 40], where $\Delta E = \sqrt{\Delta\epsilon^2 + 4t_c^2}$. Then, there will be four kinds of cotunneling processes in the DQD (see figure 5(d)). (1) The electron originally occupying ϵ^- tunnels to the lead RD (LD), and another electron at $V_{RD} + \Delta E$ ($V_{LD} + \Delta E$) in the lead LS (RS) tunnels to ϵ^+ . (2) The electron at the state ϵ^+ tunnels to the lead LD (RD), and another electron at $V_{LD} - \Delta E$ ($V_{RD} - \Delta E$) in the lead RS (LS) tunnels to ϵ^- . (3) The electron at the state ϵ^+ tunnels to the drain lead LD (RD), and another electron at V_{LD} (V_{RD}) in the source lead LS (RS) tunnels to ϵ^+ . (4) The electron at ϵ^- tunnels to the lead LD (RD), and another electron at V_{LD} (V_{RD}) in the lead LS (RS) tunnels to ϵ^- . Here, although the cotunneling processes may be similar to that discussed in [8], the conductance is totally different. In [8], the system is a serial DQD. When $t_c = 0$, since there is no transport coupling between the two QDs, I and $\frac{dI}{dV}$ are zero exactly. In the present system, because each QD is connected to its own source and drain leads, I and $\frac{dI}{dV}$ are nonzero, no matter $t_c = 0$ or $t_c \neq 0$.

Figure 5(a) shows the conductance G_{LS} as a function of the voltage V_{LS} by changing V_{LS} and V_{RS} simultaneously, i.e., $V_{LS} = V_{RS}$. For $t_c = 0$, the Kondo peaks locate at $V_{LS} = \pm\Delta\epsilon$. When t_c is increased, the two Kondo peaks move to $V_{LS} = \pm\Delta E$. Thus, they could emerge in larger $|V_{LS}|$ with increasing t_c . These two peaks correspond to the first and second kind of the cotunneling processes as discussed in the above paragraph. In addition, another small Kondo peak and dip emerge at $V_{LS} = 0$, which is attributed to the third and fourth kind of the cotunneling processes. Notice that in the third and fourth kind of the cotunneling processes, the original and final electrons are at

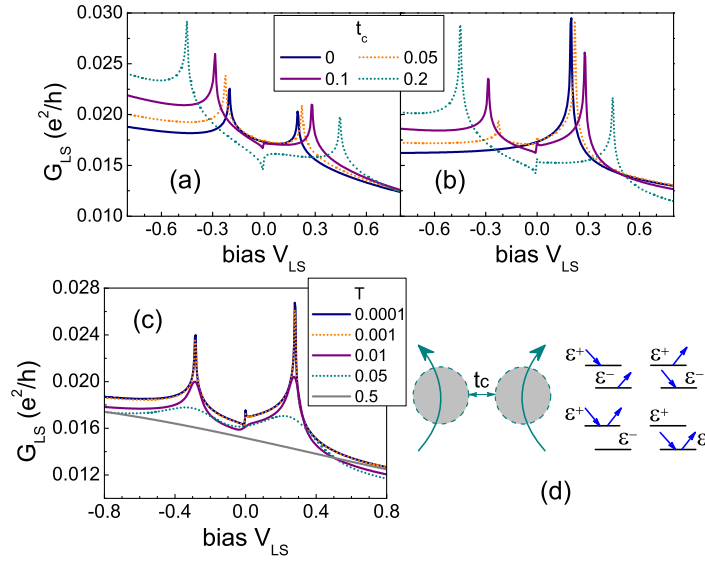


Figure 5. (a) and (b) Conductance G_{LS} as a function of the voltage V_{LS} at different t_c . In (a), V_{LS} and V_{RS} are changed simultaneously, with $V_{LD} = V_{RD} = 0$. In (b), only V_{LS} is changed, with $V_{RS} = V_{LD} = V_{RD} = 0$. The temperature is $T = 0.001$. (c) G_{LS} as a function of V_{LS} at different temperature T . In (c), only V_{LS} is changed, with $V_{RS} = V_{LD} = V_{RD} = 0$ and $t_c = 0.1$. The remaining parameter is $\bar{\epsilon} = -5.0$. (d) Schematic diagram of the four cotunneling processes between the molecular states and the leads.

the same molecular state. Thus, the Kondo peak and the dip is always fixed around $V_{LS} = 0$. Figure 5(b) shows G_{LS} as a function of V_{LS} when only V_{LS} is changed and $V_{LD} = V_{RS} = V_{RD} = 0$. At $t_c = 0$, there is only one Kondo peak at $V_{LS} = \Delta\epsilon$, which is the pseudospin-resolved Kondo peak observed in the experiment of [14]. However, when t_c is increased, this peak moves to $V_{LS} = \Delta E$. Besides, the Kondo peak at $V_{LS} = -\Delta E$ also emerges, and its height becomes higher and higher. The reason is that at $t_c \neq 0$, the electron at the molecular state ϵ^- (ϵ^+) can tunnel to both left and right drain leads, and the electron in the left and right source leads can tunnel to the molecular state ϵ^- (ϵ^+). This is different from $t_c = 0$, in which the electron at the level ϵ_L (ϵ_R) can only tunnel to one drain lead LD (RD). Additionally, a small peak and a small dip emerge around $V_{LS} = 0$, because of the third and fourth kind of the cotunneling processes. In figure 5(c), we show the dependence of G_{LS} on temperature T . It can be clearly seen that with increasing T , the height of the Kondo peak becomes lower and lower. At $T = 0.5$, all of the Kondo peaks disappear.

Next, we investigate the conductance G_{LS} as a function of the pseudospin splitting energy $\Delta\epsilon$ at different t_c . In figure 6(d), the voltages are set to $V_{LS} = 0.2$ and $V_{RS} = V_{LD} = V_{RD} = 0$. At $t_c = 0$, there are two Kondo peaks at $\Delta\epsilon = 0$ and $\Delta\epsilon = V_{LS}$. With increasing t_c , the original peak at $\Delta\epsilon = V_{LS}$ moves toward $\Delta\epsilon = 0$ and the height is decreased, because this Kondo peak now locates at $\sqrt{\Delta\epsilon^2 + 4t_c^2} = V_{LS}$. The other Kondo peak emerges at the symmetric place of the other side of $\Delta\epsilon$. In addition, the peak at $\Delta\epsilon = 0$ broadens and the height is declined. If t_c is gradually increased,

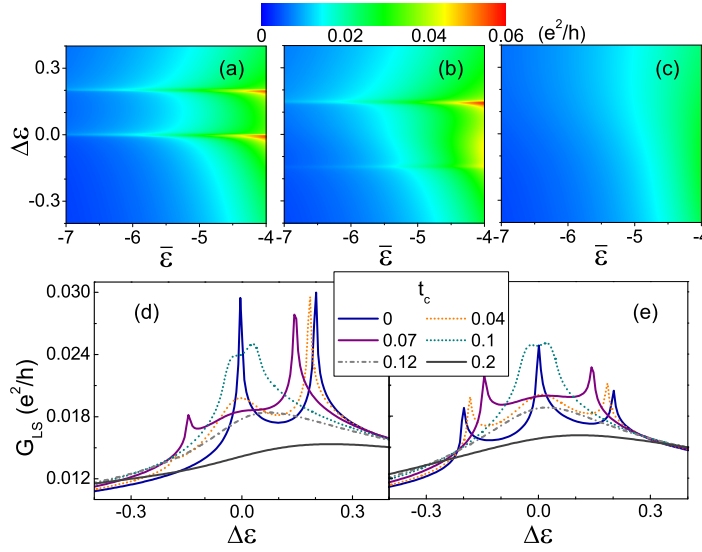


Figure 6. (a)-(c) Conductance G_{LS} as functions of $\bar{\epsilon}$ and $\Delta\epsilon$. The source and drain voltages are set to $V_{LS} = 0.2$ and $V_{RS} = V_{LD} = V_{RD} = 0$. t_c is taken as 0, 0.07, and 0.2 in (a), (b), and (c), respectively. (d) and (e) show G_{LS} as a function of $\Delta\epsilon$ at different t_c with $\bar{\epsilon} = -5.0$. In (d), $V_{LS} = 0.2$ and $V_{RS} = V_{LD} = V_{RD} = 0$; in (e), $V_{LS} = V_{RS} = 0.2$ and $V_{LD} = V_{RD} = 0$. The temperature is $T = 0.001$.

the height of the peak at $\Delta\epsilon = 0$ is decreased. At the same time, the two peaks at the opposite sides of $\Delta\epsilon$ move toward $\Delta\epsilon = 0$, and eventually mix together at $\Delta\epsilon = 0$. Thus, there is only one broadening peak around $\Delta\epsilon = 0$. Then, by further increasing t_c , the height of this broadening peak decreases until this peak vanishes. This is attributed to the fact that the two quantum dots become a whole when t_c is considerably large. The degeneracy of the pseudospin does not exit, so does the Kondo effect. Figures 6(a)-6(c) are the two-dimensional plot of the conductance G_{LS} versus $\Delta\epsilon$ and $\bar{\epsilon}$ with $t_c = 0, 0.07$, and 0.2 , respectively. The change of the color in figures 6(a)-6(c) clearly shows the process discussed above. As a comparison, figure 6(e) shows G_{LS} as a function of the pseudospin splitting energy $\Delta\epsilon$ when $V_{LS} = V_{RS} = 0.2$ and $V_{LD} = V_{RD} = 0$. It is clear that at $t_c = 0$, except for the peak at $\Delta\epsilon = 0$, there are two Kondo peaks at both sides of $\Delta\epsilon$. When t_c is increased, the peak at $\Delta\epsilon = 0$ becomes lower and boarder; and the peaks at both sides move toward $\Delta\epsilon = 0$, and eventually mix together. If t_c is gradually increased, the last peak becomes lower till it disappears.

2.3. Pseudospin transport and pseudospin flipping current

In this subsection, we discuss the pseudospin transport in the DQD system. As we know, the direction of the real spin can be changed in the electron transport process. As a result, a steady spin current cannot be held easily. On the other hand, the measurement of the spin current is also difficult. Thus, it limits the development of the research field on the spin transport. The orbital Kondo effect, which is a pseudospin Kondo effect, can be regarded as the counterpart of the spin Kondo effect. The Kondo effect,

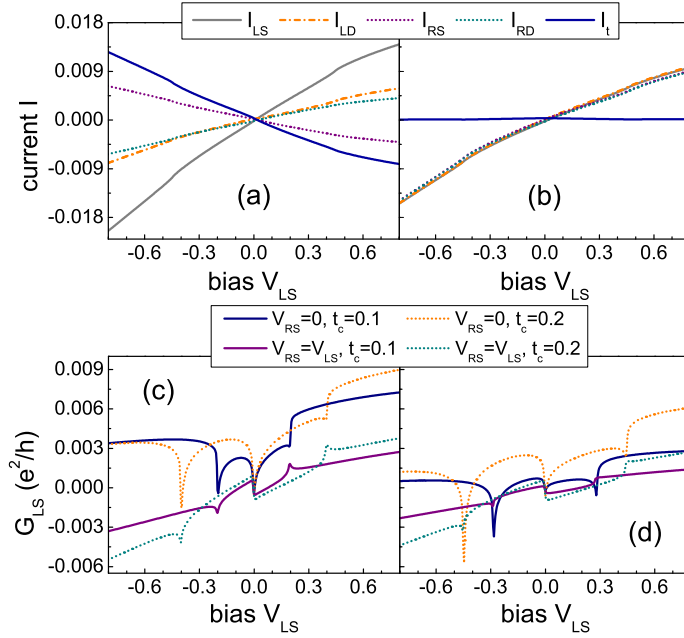


Figure 7. (a) and (b) show the current in the leads LS , LD , RS , and RD , and the pseudospin flipping current I_t as a function of V_{LS} with the pseudospin splitting energy $\Delta\varepsilon = 0.2$ and $t_c = 0.2$. In (a), only V_{LS} is changed; in (b), both V_{LS} and V_{RS} are changed with $V_{LS} = V_{RS}$. (c) and (d) show the pseudospin flipping conductance G_t as a function of V_{LS} with $\Delta\varepsilon = 0$ and $\Delta\varepsilon = 0.2$, respectively. All the unchanged source and drain voltages are set to zero, the temperature keeps $T = 0.001$, and $\bar{\varepsilon} = -5.0$.

whose emergence is originally related to the spin degree of freedom, can also be realized in the system with the orbital degree of freedom. This indicates that we may use a system, including the orbital degree of freedom, to study the physical properties which are difficult to be observed with the spin degree of freedom. In the DQD system, the current flow in the leads LS , RS , LD , and RD is easy to measure, which means that the pseudospin current is easy to measure. Furthermore, the pseudospin flipping only happens in the QDs and its flipping strength is controllable and tunable. When the current flows in the leads, it cannot tunnel from the left side (LS and LD) to the right side (RS and RD), which indicates that the pseudospin current is conserved in the leads. Thus, it is possible and convenient to use the orbital degree of freedom to study the properties related to the spin degree of freedom.

It should be pointed out that, when $t_c \neq 0$, the currents in the leads LS , LD , RS , and RD may not be equal to each other, but they still satisfy the relation $I_{LS} + I_{RS} = I_{LD} + I_{RD}$ due to the electric current conservation. Here, we define that the positive direction of the current is flowing into the DQD for the source leads and is going out from the DQD for the drain leads. Besides, we introduce the pseudospin flipping current I_t , which describes the current from the right QD to the left one. The relation between I_t and the four wire currents are $I_{LS} + I_t = I_{LD}$ and $I_{RS} - I_t = I_{RD}$.

Thus, I_t can be expressed as:

$$I_t = \frac{(I_{LD} - I_{RD}) - (I_{LS} - I_{RS})}{2} = \frac{I_D^{spin} - I_S^{spin}}{2},$$

where $I_{S/D}^{spin} \equiv I_{LS/D} - I_{RS/D}$ is the pseudospin current in the source/drain lead. Figures 7(a) and 7(b) illustrate the pseudospin flipping current I_t as a function of the voltage V_{LS} . In figure 7(a) only V_{LS} is changed, and in figure 7(b) both V_{LS} and V_{RS} are changed with $V_{LS} = V_{RS}$. It is clear that when only V_{LS} is changed, the pseudospin flipping current I_t is considerable as compared with the current in the four leads, because the pseudospin-up chemical potential eV_{LS} is not equal to the pseudospin-down one eV_{RS} , i.e., there exists a pseudospin bias $V_S^{spin} = V_{LS} - V_{RS}$. On the other hand, when both V_{LS} and V_{RS} are changed, the pseudospin flipping current I_t is negligible, because the pseudospin bias $V_{S/D}^{spin} = V_{LS/D} - V_{RS/D}$ is zero. These calculations demonstrate that if we deal with the pseudospin-resolved transport spectroscopy in the DQD system, a steady pseudospin current can be induced. The magnitude of this pseudospin current is not small, and in particular it is easy to be controlled and measured.

At last, in order to see the characteristics of the pseudospin flipping in the DQD more clearly, we calculate the flipping conductance which is defined as

$$G_t(V_{LS}, V_{LD}, V_{RS}, V_{RD}) = \lim_{V \rightarrow 0} [I_t(V_{LS} + \frac{V}{2}, V_{LD} - \frac{V}{2}, V_{RS}, V_{RD}) - I_t(V_{LS}, V_{LD}, V_{RS}, V_{RD})]/V. \quad (10)$$

Notice that in the above definition, only the left source and drain voltages are changed by $\pm V/2$. Figures 7(c) and 7(d) show G_t as a function of V_{LS} with $\Delta\varepsilon = 0$ and 0.2, respectively. The results exhibit the following features: (1) no matter whether V_{RS} is changed with V_{LS} or not, the Kondo peaks and dips of G_t emerge at $V_{LS} = 0$ and $V_{LS} = \pm\Delta E$; (2) with increasing of t_c , G_t is enhanced in usual; (3) the dips are much sharper when V_{LS} is changed only, which also indicates that we can focus on the pseudospin-resolved transport spectroscopy when we study the pseudospin flipping current in the parallel DQD systems.

3. Conclusion

In this paper, we investigate the orbital Kondo effect in a parallel double quantum dot. When the interdot tunneling coupling t_c is zero, we explain the pseudospin-resolved results observed in the recent experiment [14]. We find that there exist three Kondo peaks and two Kondo peaks in the curve of the conductance versus the pseudospin splitting energy for the pseudospin-non-resolved case and the pseudospin-resolved case, respectively. When the interdot coupling t_c is nonzero, the levels in the separated quantum dots can hybridize into the molecular levels, and new Kondo peaks emerge. In addition, the pseudospin flipping current and the conductance are also studied, and both of them show the Kondo peaks and dips. We point out that the present pseudospin system has many advantages in comparison with the real spin system. In the pseudospin system, the chemical potential of each pseudospin component, the pseudospin splitting

energy, and the coupling strength can be well controlled and tuned. Besides, the pseudospin current is conserved in the source and drain leads, and the pseudospin-up and pseudospin-down currents can individually be measured. Therefore, we believe that these results could be observed in the present technology.

Acknowledgements

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References

- [1] Hewson A C 1993 *The Kondo Problem to Heavy Fermions* (Cambridge: Cambridge University Press)
- [2] Kouwenhoven L and Glazman L 2001 *Phys. world* **14** 33
- [3] Inoshita T 1998 *Science* **281** 526
- [4] van der Wiel W G, De Franceschi S, Fujisawa T, Elzerman J M, Tarucha S and Kouwenhoven L P 2000 *Science* **289** 2105
- [5] Goldhaber-Gordon D, Shtrikman H, Mahalu D, Abusch-Magder D, Meirav U and Kastner M A 1998 *Nature (London)* **391** 156
- [6] Cronenwett S M, Oosterkamp T H and Kouwenhoven L P 1998 *Science* **281** 540
- [7] Sasaki S, De Franceschi S, Elzerman J M, van der Wiel W G, Eto M, Tarucha S and Kouwenhoven L P 2000 *Nature (London)* **405** 764
- [8] Sun Q -F and Guo H 2002 *Phys. Rev. B* **66** 155308
- [9] Wilhelm U, Schmid J, Weis J and von Klitzing K 2002 *Physica E* **14** 385
- [10] Holleitner A W, Chudnovskiy A, Pfannkuche D, Eberl K and Blick R H 2004 *Phys. Rev. B* **70** 075204
- [11] Jarillo-Herrero P, Kong J, van der Zant H S J, Dekker C, Kouwenhoven L P and De Franceschi S 2005 *Nature (London)* **434** 484
- [12] Schröder D M, Hüttel A K, Eberl K, Ludwig S, Kiselev M N and Altshuler B L 2006 *Phys. Rev. B* **74** 233301
- [13] Makarovski A, Liu J and Finkelstein G 2007 *Phys. Rev. Lett.* **99** 066801
- [14] Amasha S, Keller A J, Rau I G, Carmi A, Katine J A, Shtrikman H, Oreg Y and Goldhaber-Gordon D 2013 *Phys. Rev. Lett.* **110** 046604
- [15] Tosi L, Roura-Bas P and Aligia A A 2013 *Phys. Rev. B* **88** 235427
- [16] Nishikawa Y, Hewson A C, Crow D J G and Bauer J 2013 *Phys. Rev. B* **88** 245130
- [17] Keller A J, Amasha S, Weymann I, Moca C P, Rau I G, Katine J A, Shtrikman H, Zaránd G and Goldhaber-Gordon D 2013 *Nature Phys.* **10** 145
- [18] Büsser C A, Feiguin A E and Martins G B 2012 *Phys. Rev. B* **85** 241310(R)
- [19] Vernek E, Büsser C A, Anda E V, Feiguin A E and Martins G B 2014 *Appl. Phys. Lett.* **104** 132401
- [20] Hübel A, Held K, Weis J and von Klitzing K 2008 *Phys. Rev. Lett.* **101** 186804
- [21] Okazaki Y, Sasaki S and Muraki K 2011 *Phys. Rev. B* **84** 161305(R)
- [22] Fujisawa T, Hayashi T, Cheong H, Jeong Y and Hirayama Y 2004 *Physica E* **21** 1046
- [23] Petersson K D, Petta J R, Lu H and Gossard A C 2010 *Phys. Rev. Lett.* **105** 246804
- [24] Feinberg D and Simon P 2004 *Appl. Phys. Lett.* **85** 1846
- [25] Carmi A, Oreg Y and Berkooz M 2011 *Phys. Rev. Lett.* **106** 106401
- [26] López R, Sánchez D, Lee M, Choi M -S, Simon P and Le Hur K 2005 *Phys. Rev. B* **71** 115312
- [27] Borda L, Zaránd G, Hofstetter W, Halperin B I and von Delft J 2003 *Phys. Rev. Lett.* **90** 026602

- [28] Oosterkamp T H, Janssen J W, Kouwenhoven L P, Austing D G, Honda T and Tarucha S 1999 *Phys. Rev. Lett.* **82** 2931
- [29] Kouwenhoven L P, Oosterkamp T H, Danosastro M W S, Eto M, Austing D G, Honda T and Tarucha S 1997 *Science* **278** 1788
- [30] Stafford C A and Wingreen N S 1996 *Phys. Rev. Lett.* **76** 1916
- [31] Sun Q -F, Guo H, and Wang J 2003 *Phys. Rev. Lett.* **90** 258301
- [32] Wang D -K, Sun Q -F and Guo H, 2004 *Phys. Rev. B* **69** 205312
- [33] Meir Y, Wingreen N S and Lee P A 1991 *Phys. Rev. Lett.* **66** 3048
- [34] Sun Q -F, Guo H and Lin T -H 2001 *Phys. Rev. Lett.* **87** 176601
- [35] Sergueev N, Sun Q -F, Guo H, Wang B G and Wang J 2001 *Phys. Rev. B* **65** 165303; Sun Q -F and Guo H 2001 *Phys. Rev. B* **64** 153306
- [36] Kiselev M N, Kikoin K and Molenkamp L W 2003 *Phys. Rev. B* **68** 155323
- [37] Crisan M and Grosu I 2010 *Physica E* **42** 2446
- [38] Kiseleva M N, Kikoinb K A and Molenkampc L W 2004 *J. Magn. Magn. Mater.* **272** 1676
- [39] Oosterkamp T H, Fujisawa T, van der Wiel W G, Ishibashi K, Hijman R V, Tarucha S and Kouwenhoven L P 1998 *Nature (London)* **395** 873
- [40] Sun Q -F, Wang J and Lin T -H 2000 *Phys. Rev. B* **61** 12643